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INSTRUMENTAL DETERMINATIONS OF THE CHARACTERISTICS OF TURBULENT EXCHANGE IN THE OCEAN

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Introduction

The basic characteristics of the process of turbulent intermixing in the sea and ocean are determined by irregular, random fluctuations of the rate of flow, temperature and other properties of sea-water. Measurement of the magnitudes of hydrologic turbulent pulsations, study of the correlation between them at various points in the current and at different moments in time permit studying the internal mechanism of the process and give a direct method of determining the numerical characteristics of turbulent exchange. At the present time a series of works is known which are dedicated to direct determination of some of the characteristics of turbulence in oceans [e.g., 1, 2, 3]. In recent years a series of models of turbulimeters has been created in the Department of Physics of Ocean and Land Waters of the faculty of Physics of Moscow University, destined for use under various conditions.

This paper contains information about research performed with the help of the fourth model of the turbulimeter on turbulent intermixing in the surface layer of waters of the Antarctic sector of the Indian and Pacific Oceans. The research was done during the third voyage of the Naval Antarctic Expedition on the diesel-electric vessel "Ob'" in January - February, 1958.

Statement of the Problem and Method of Investigation

Current theories of turbulent intermixing originate from examination of the statistical features of horizontal and vertical fluctuations of components of the rate of flow and temperature of the water. Such values as transfer of the amount of movement, the heat, the coefficients of turbulent exchange and the scale of turbulent heterogeneities are determined by application of correlative analysis to the field of velocities and temperatures. It was our task to obtain all the enumerated characteristics on the basis of continuous measurement of the fluctuations of both components, water velocity and temperature.

The investigations of turbulence were made using a model of the turbulimeter adapted for making measurements on board a ship.

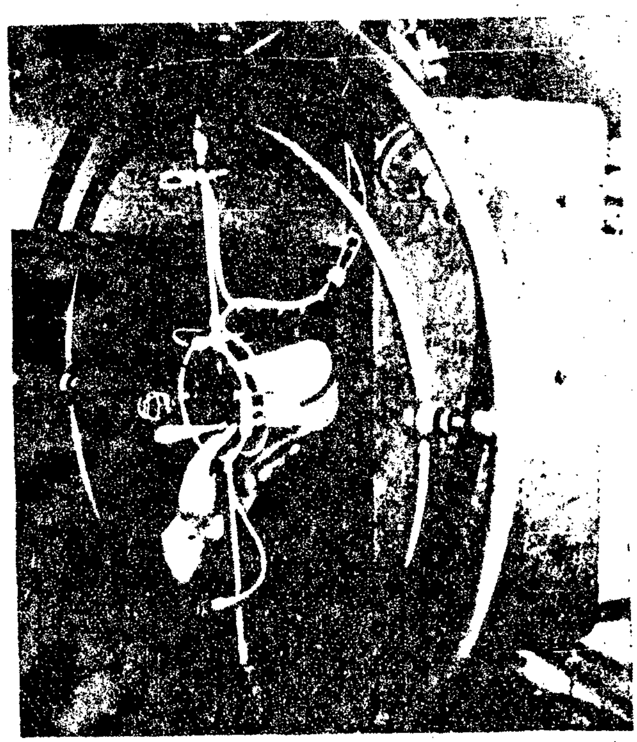

Fig. 1. Fourth model of turbulimeter (TM-4).

Figure 1 is a photograph of this turbulimeter (TM-4). A light vane is set at the center of the ring of the turbulimeter on agate bearings (1); it is intended for orientation of the receiver of pulsations of horizontal and vertical components of the velocity (2) of large scale fluctuations of the current. Set on the same level is a receiver of pulsations and the mean temperature of the water (3), thus presenting a combination thermistor and thermobattery. As protection against possible mechanical injury, the receiver is provided with a protective grill. Two other thermistors (4) are fastened to a vertical post; the distance between them can be set within the limits of the dimensions of the post. This is needed for investigation of the turbulent structure of the current. In measuring the pulsation of the components of the velocity of the current it is important to assure a vertical position of the instrument. If at the time of measurement there is drifting of the boat or greater velocity of the stream considerable angles of inclination of the cable are possible, causing lowering of the instrument and consequently an inclination of the frame of the turbulimeter (5). Within the frame, on divided axles, the ring bearing all the receivers is suspended. It is balanced in such a way that it tends to assume a vertical position in the current. The receiver (8) serves for registration of vertical movement of the instrument during rocking of the boat from which the measurements are being made. The effect of rocking motion of the boat on the registration of turbulent pulsations which make up the velocity of the current is eliminated by adding it to the measuring arrangement of the receiver.

Instrument TM-4 thus permits making simultaneous registration of seven elements. Continuous registration of changes in magnitude is done with a loop oscillograph.

To register the pulsations which make up the velocity of the current a thermohydrometer is used, measuring both components at practically the one point. The sensitivity of a receiver at a corresponding rate of delivery to measuring equipment and the matching of the loop can be changed within broad limits. In our measurements it varied from 2-3 to 0.05 mm/sec per mm of the oscillograph scale, depending on the amount of the mean velocity. Temperature pulsations were registered with a sensitivity of about 0.002°. In separate measurements, using an especially sensitive train, we attained sensitivities of 0.0002-0.0004° per mm of the oscillograph scale. The type of receivers used and the frequency characteristics of the loops assured practically unaltered recording of the turbulence frequencies of temperature fluctuations from 7-10 hertz to 0.03-0.05 hertz (that is, a duration of 20-30 seconds). The lower limit of the frequencies is determined by the inertness of the outer layers of the thermobatteries (for more detail see [4]). The measured frequencies of the pulsations lie in a range from the same 10 hertz (which is determined already by the loop's own frequency) to very slow oscillations whose periods are comparable with the duration of the measurement.

The turbulimeter was let down by means of a hydrologic windlass of the "Ocean" on a steel cable, parallel to which there was another cable connecting the instrument's receiver with the registering part of the apparatus set up in a hydrologic laboratory on deck. Power supply of the measuring arrangements was accomplished from dry cells and accumulators placed in a compartment especially built for this purpose.

Results of the Observations

The measurements were made during the season of the hydrologic stations or in the working period of the aerial photographic survey group, combined with a long stay of the boat at the land floe and at a detached iceberg. Studies of turbulence were made at the surface of the ocean waters both to the layer of greatest stability and below it. The maximum depth to which the instrument was lowered was 45 meters. On the average the duration of a recording was about five minutes. The vertical distribution of the basic characteristics of the turbulent process were determined, and the question of the time of their change at a given level was also studied. For this purpose a series of measurements of the previously mentioned magnitudes was made, for which the turbulimeter was held at a given depth (with periodic switching on of the oscillograph) for two or more hours.

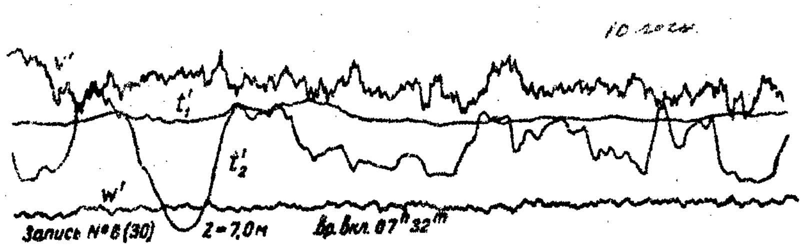

Fig. 2. Specimen of the record of turbulent pulsations at a depth of seven meters.

Figure 2 gives a specimen of the record of turbulent pulsation at the 7-meter level on 19 January at station No 330. In it W' and V' are the vertical and horizontal components respectively of the velocity, recorded at a somewhat different sensitivity of the loops; t_1' and t_2' are records of temperature pulsations at two levels 0.5 meter apart. Curve t_2' corresponds to a measurement sensitivity of $3.1 \cdot 10^{-4\circ}$ per mm of the oscillograph scale. The temperature pulsations at the second level were registered with a sensitivity of a slightly lower degree. The mean-square values of the temperature pulsations corresponding to this registration equal $3.9 \cdot 10^{-3\circ}$, those of the pulsations of the vertical components of the current's velocity, causing intermixing along the vertical, 1.2 cm/sec. The ratio between the mean-square values of the vertical pulsations and the horizontal components of the velocity was found to equal 0.86. The mean velocity here was in the order of 20 cm/sec. On the oscillograph the time scale is from the right.

Visual observations on the oscillograph screen of velocity and temperature pulsations permits setting up a qualitative representation of the nature of the change in intensity of turbulence. The amplitude of turbulence grows with depth, attaining a well-defined maximum at the layer of the largest temperature and velocity gradients. Below this layer it decreases sharply and it does not change very much from there on. Such a character of the fluctuation field is observed by us at all stations when the layer of skipping is more or less defined. In studying the statistical regularities of the fluctuations we find it possible to determine all the most important characteristics of the process of turbulent intermixing.

A total of 177 oscillographic recordings was obtained of the whole complex of values, 97 in the Indian and 80 in the Pacific Ocean.

Statistical processing of the observational material was done using an electromechanical correlator. As a result of the processing the numerical characteristics of turbulent interchange were obtained, along with quantitative regularities of their changes with depth.

Figure 3 gives curves of the distribution along the vertical of the mean-square values for pulsations of temperature and vertical components of the velocity of the current, and likewise the distribution by depth

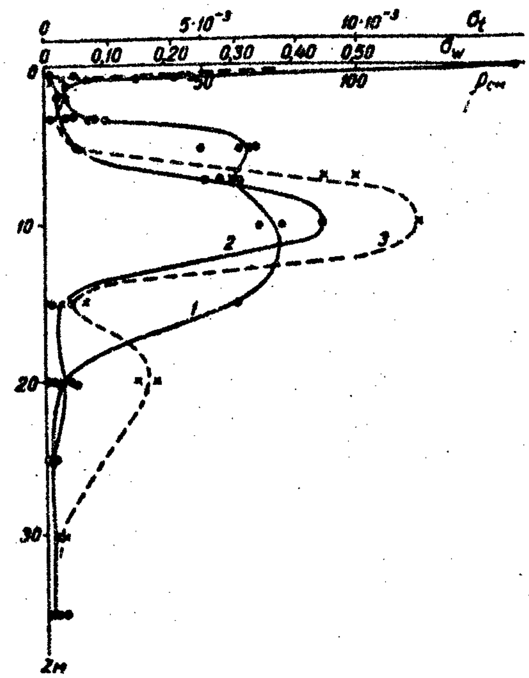

Fig. 3. 1. Mean-square values for pulsations of temperature of the water in degrees (σ_t); 2. Mean-square values for pulsations of the vertical components of the rate of flow in cm/sec (σ_w); 3. Horizontal scale of turbulence in cm (ρ).

of the horizontal dimensions of the turbulent formation -- the turbulence scales -- found according to the correlation function of temperature fluctuations. The curves were plotted from the data of station No 332, taken 25-26 January in the region of the Land of Discovery In the season of the station the wind velocity did not exceed 5-7 m/sec, the air temperature was on the average 4° below the temperature of the surface of the water and gradually declined. A thin crust of fresh ice was formed on the surface of the water. The boat was immobile and vibration of the body associated with operation of the engine was absent. The hydrologic daily station was made parallel with our work. According to the bathometric data the salinity of the water increases almost linearly with depth. The water temperature at the surface was -1.18° and at a depth of 10 m had fallen to -1.29°. It fell further to -1.70° and then at a depth of 100-150 m went down to -1.80°. Thus, at a depth of 10-12 m there was a more or less defined jump in density. Some warming and freshening of the surface layer of the waters was caused by summer melting of ice in the region of the investigations.

The hydrologic system was indeterminable. According to the data of the printing vane BPV-2 set up at the 50 m level the mean velocity of the current slowly changes from 0 to 6-8 cm/sec. Analogous smooth oscillations are presented by the mean water temperature. Thus, at the 10 m level the water temperature varies in the course of four to six hours around a mean value of -1.29° with an amplitude of up to 0.5°.

Measurements of the turbulent fluctuations of the horizontal and vertical components of the velocity of the current and the water temperature permit judging the intensity of the processes of intermixing under given conditions. The mean square values given in the figure for pulsations of the water temperature and the vertical component of the rate of flow, determined during a prolonged series, attained the largest values with approach to the layers with the largest gradients of density. Here they equal 6.0-7.0 . 10^{-30} and 0.4-0.5 cm/sec respectively. The maximum dimensions of the turbulent vortices, 100-120 cm, took place at the same depths. Below this layer the mean square values of the pulsations of temperature and velocity decrease rapidly with depth to a very small value.

We obtained by the direct method numerical values for the turbulent flow of heat in the vertical and tangential frictional stress. According to the hypothesis of the course of intermixing, the maximum flows of heat and maximum amounts of motion caused by turbulent interchange should be observed at the depth of the largest values on the scales of turbulence and the mean square values for pulsations of the vertical component of the rate of flow.

According to our measurements the maximum heat flow at a depth of 10 m is 12.0-15.0 . 10^{-3} cal/cm^2 sec. The tangential frictional stress, representing flow of the quantity of motion, changes within very narrow limits from 3.0-5.0 . 10^{-3} to 0.57 dynes/cm^2, assuming the largest values to be in the layers with large gradients of the mean velocity (Fig. 4).

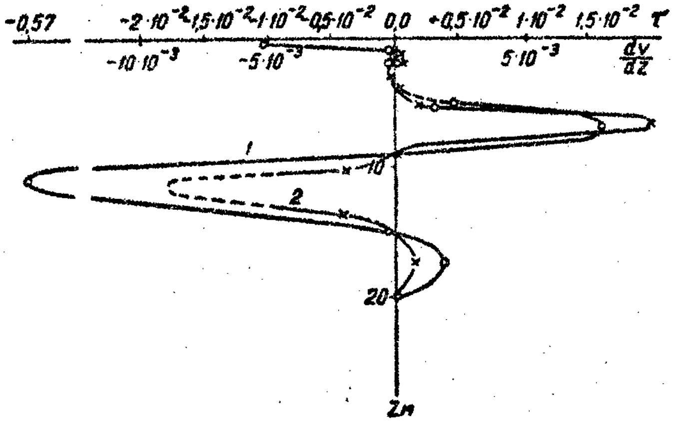

Fig. 4. 1. Tangential direction of turbulent frictional stress in dynes/cm^2; 2. Gradient of the mean rate du/dz in sec^{-1}.

Fig. 5a.

$$K_T = -\frac{\overline{W' t'}}{\overline{d t}/dz}$$

$$\nu = -\frac{W' V'}{\overline{dV}/dz}$$

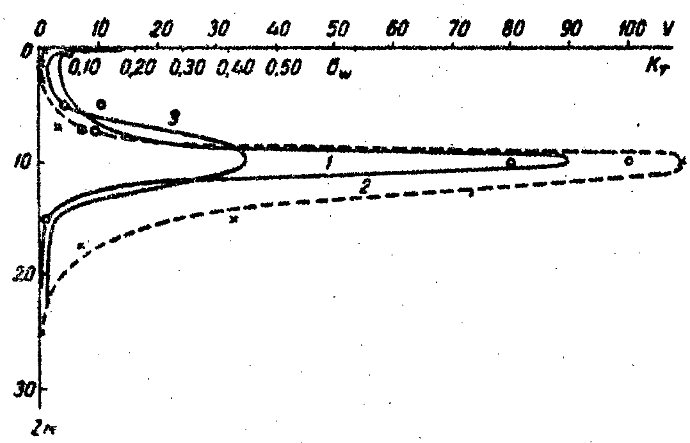

Fig. 5b. 1. --O-- turbulent viscosity in absolute units; 2. --X-- coefficient of turbulent exchange K_T along the verticals in absolute units; 3. Mean-square values of pulsations of vertical components of the rate of flow σ_ω in cm/sec.

In measuring the gradients of the mean velocity and temperature along the verticals we calculated the value for the turbulent heat exchange coefficient K_T and for the transfer coefficient of the amount of motion (turbulent viscosity) on the basis of the formal hypothetical relationships of the exchange coefficients.

In Figure 5 the results of these calculations are presented in the form of graphs of the vertical distribution of the coefficients. The same graph contains a curve of the distribution by depth of fluctuation of the vertical component of the rate of flow. A sharp, clearly-defined expression of the maximum of the exchange coefficients is observed in the depth of the greatest intensity of turbulence. The data we obtained are insufficient for complete presentation of the comparative course of the coefficients of turbulent heat exchange and viscosity. On the basis of the graph, however, it is possible to judge the qualitative resemblance in the character of the change of both values with depth.

Conclusions

The basic values were found which characterize the processes of turbulent intermixing in the surface layer of waters of the Antarctic sector of the Indian and Pacific Oceans in the summer period under conditions of the melting of ice. Certain regularities of their distribution along the vertical and the nature of their change with time were determined. The investigations which were made clarify certain aspects of the complex interrelation between the mean and pulsation characteristics in the field of velocity and temperature. But final and sufficiently complete quantitative ideas about the formation of the average hydrologic system under the influence of the micro-characteristics of the turbulent field can only be obtained by careful analysis and generalization of the materials obtained by experimental research on the processes of turbulent exchange which occur in very varied natural conditions.

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